NRL Report 6456

# Magnetically Induced Nonequilibrium Electron Temperatures

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November 23, 1966

NAVAL RESEARCH LABORATORY
Washington, D.C.

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## ABSTRACT

For operation of an MHD generator at low temperatures, various methods have been proposed to enhance the ionization and hence the conductivity. This report considers the scheme in which the electrons present in an MHD generator are accelerated by the magnetic field itself (to a "magnetically induced nonequilibrium temperature") preparatory to producing additional electrons by impact ionization. A model for the flow of a partially ionized gas in an MHD generator that combines extreme mathematical simplicity with at least qualitative physical realism is used. The derivations show that the electron temperatures attained cannot exceed the temperature that the gas had before part of its kinetic energy was converted into motion along the channel; that is, the magnetically induced nonequilibrium electron temperature cannot exceed the stagnation temperature of the gas, which is equal to the temperature of the gas at rest before being expanded through a nozzle.

## PROBLEM STATUS

This is an interim report on a continuing problem.

## AUTHORIZATION

NRL Problem P03-07
Project RR 008-03-46-5676

Manuscript submitted June 30, 1966.

MAGNETICALLY INDUCED NONEQUILIBRIUM
ELECTRON TEMPERATURES

## DISCUSSION

Consider a partially ionized gas moving with a velocity $U$ in the $x$ direction through a "channel" (a region bounded by a square or cylindrical tube as shown in Fig. 1) upon which a magnetic field in the $z$ direction has been impressed. There are for our purposes, three species of particles present — electrons, positive ions, and neutral atoms; the number of electrons is assumed equal to that of the number of ions, and that of the neutrals is assumed to be much larger than either. It is well known that a magnetic field $B$ deflects a particle of charge $e$ and mass $m$ moving perpendicular to it, causing it to move in a circle of radius $r = mv/eB$ (Larmor radius) with frequency $\omega = eB/m$ (Larmor frequency or cyclotron frequency). In practical cases, the magnetic field strength is usually such that for ions $\omega$ is very low and $r$ is very large, so that we can assume that only the electrons are caused to spiral by the magnetic field; the ions (and, of course, the neutrals) are essentially unaffected by the magnetic field.

In the absence of collisions between the species, the device thus acts in the language of Zener (1), as a "magnetic sieve": The ions pass through the channel, while the electrons are compelled to stay behind by the magnetic field which causes them to spiral rather than proceed forward. Charge separation thus occurs, and if an external load is connected from the front of the channel to the back, as shown in Fig. 2, then an electric current will flow through it. In the literature (2), such device is usually called a "magnetohydrodynamic generator operating in the Hall mode" rather than "magnetic sieve." In practice, collisions between species will never be wholly absent, but as long as electron-neutral collisions are infrequent (time between collisions $\tau$ much larger than $\omega^{-1}$, or $\omega\tau >> 1$), the device will continue to operate basically in the same manner, for each electron will perform several complete Larmor circles and thus get appreciably behind the stream of ions that is moving forward, between any two collisions.

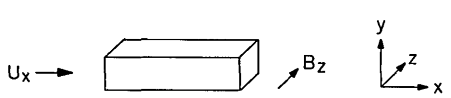


Fig. 1 - MHD channel without any electrical connections

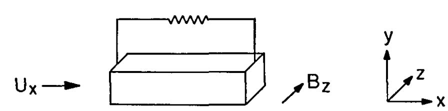


Fig. 2 - MHD channel connected as a Hall generator (magnetic sieve)

When, on the other hand, the collision frequency is large compared to the Larmor frequency ($\omega\tau << 1$), the situation is quite different: each electron collides with a neutral particle long before completing a Larmor circle; it therefore loses little of its forward speed, but it is slightly deflected to the left between any two collisions. The device may thus be called a "magnetic deflector"; more commonly it is called a "MHD generator operating in the Faraday mode"; if we want to get a current to flow through an external load, we must now connect the latter as shown in Fig. 3, perpendicular to both $U$ and $B$.

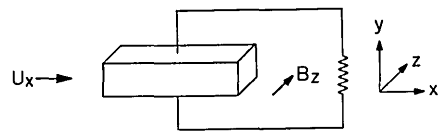


Fig. 3 - MHD channel connected as a Faraday generator (magnetic deflector)

In practice, $\omega\tau$ is likely to be neither much smaller nor much larger than unity, and the direction of optimum conduction of external current will then be neither parallel to $U$ (as in the ideal magnetic sieve) nor perpendicular to $U$ (as in the ideal magnetic deflector) but at an angle oblique to $U$. We need not discuss here the various schemes for external current connections that have been proposed (2); suffice it to say that the language used to describe the physical situation gets quite complicated for these cases; the currents and voltages in the direction perpendicular to $U$ (the $y$ direction in Figs. 1-3) are called "primary" or "Faraday" currents and voltages (evidently for reasons of historical accident); those parallel to $U$ are called "Hall" currents or fields, by not completely applicable analogy with conduction in solids, and "forces" tending to "change" the electrons path from its "primary" ($y$) direction are sometimes called Hall forces and sometimes $J \times B$ forces.

So as to be perfectly clear about the model we have established and on which our calculations in the next section will be based, let us repeat that we deal nominally with three species (electrons, ions, and neutrals, with the last greatly predominating in number). These move with a random (thermal) velocity, upon which a gross gas velocity $U$ is superimposed. The sole effect of the applied magnetic field is that the electrons, but not the ions or atoms, move in circular (or spiral) paths between collisions; the only collisions we explicitly consider are between the neutrals and the electrons. These two processes, we assert, are sufficient to give a qualitative description sufficient for our purposes of the behavior of the ionized gas in the magnetic field. All the many complex mechanical and electromagnetic effects are thus included fully in the two parameters $\omega$ and $\tau$; in particular, coulomb effects between charged particles are included in the collision process between electrons and neutrals; for in practice it is believed that the direct interaction takes place between heavy ions and neutrals, with the former communicating the effects of these collisions electromagnetically to the electrons. The time $\tau$ between electron-neutral collisions serves thus as an effective parameter to describe all effects present and we shall, in our calculation, further simplify by treating these collisions in the simplest possible way, as hard-sphere ones. The justification for these simplifications is discussed by Arzimovich (3).

The question we shall study is the energy changes in the electrons as they pass through the channel. The motivation for our interest is the need, in MHD generators operating at comparatively low temperature, of producing more ionization and higher conductivity than equilibrium conditions would provide; magnetically induced nonequilibrium electron temperatures high enough to cause such additional ionizations has been proposed as one of the methods for attaining this (4). We shall see that as the electron passes through the magnetic field and undergoes collisions, its energy will, on the average, increase, but only until it reaches a limiting energy defined by the stagnation temperature of the gas.

## CALCULATIONS

### Collision Model

We consider the collision of a particle of mass and velocity $m, v$ with a particle of mass and velocity $M, V$; we assume $V = V_r + U$ with $V_r$ random and $U = U_x$ in the $x$ direction and $v(t) = P(t)v(0)$ and $v(0) = v_r + U$, $v_r$ again being random and $P(t)$ an operator describing the action of the magnetic field on the light particle (the electron). Our question will be the average gain or loss of energy of the electron.

The answer will be that the electron gains energy from the heavy particle unless the electron's initial energy is already substantially higher than that of the heavy particle; a few qualitative words may be in place, as some readers may wonder how such an asymmetry can come about, or how, to put the same matter differently, a magnetic field can accelerate an electron (it being well known, from electromagnetic theory as well as from the design of accelerators, that the direct deflecting action of a magnetic field on a charged particle leaves the particle's energy unchanged and that an additional electric field is needed to produce acceleration). The process is a two-stage one: the magnetic field deflects the electron (away from its predominantly forward motion) while leaving its energy unchanged; the subsequent collision imparts to this now random motion a predominantly forward component, and in order to do this it must increase the electron's energy. (In the more conventional terminology, the acceleration of the electron is attributed to the induced electric "Hall field.")

We consider the system of two colliding particles first in the center-of-mass system. We call $c$ and $C$ the velocities of $m$ and $M$ in the center-of-mass system before the collision and $c'$ and $C'$ the velocities in the same system after collision. The velocity of the center-of-mass system in the laboratory is called $g$, so that

$$c = v + g, \quad c' = v' + g, \quad C = V + g, \quad C' = V' + g \tag{1}$$

(with $v, v'$ the velocities of $m$ in the laboratory system). The center-of-mass system is defined by the vanishing of the total momentum,

$$mc + MC = 0. \tag{2}$$

Finally we know that after the collision, the total momentum in the center-of-mass system will still be 0; i.e., the particles will move off in opposite directions with velocities differing from the original ones in direction, but not in magnitude (Fig. 4); we can therefore write

$$c' = A(\theta, \phi)\, c. \tag{3}$$

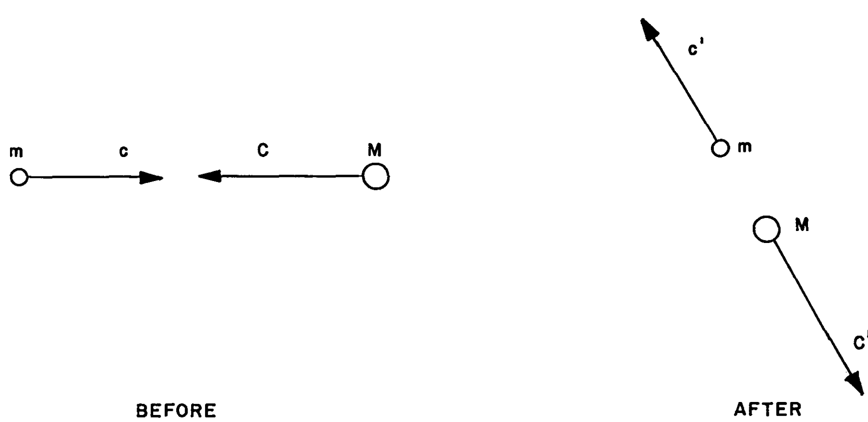


Fig. 4 - Hard-sphere collision in the center-of-mass system

We use matrix notation throughout, i.e.,

$$c = \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix}, \quad c^* = (c_x\, c_y\, c_z),$$

etc. The matrix $A$ is defined as

$$A = \begin{pmatrix} \cos\theta\cos\phi & \cos\theta\sin\phi & \sin\theta \\ -\sin\phi & \cos\phi & 0 \\ -\sin\theta\cos\phi & -\sin\theta\sin\phi & \cos\theta \end{pmatrix}, \tag{4}$$

with $\theta$ and $\phi$ the angles, generally indeterminate, of scattering in the center-of-mass system. We can now use Eqs. (2) and (1) to calculate

$$g = -(V + \gamma v)/(1+\gamma) \quad \text{where } \gamma = m/M.$$

Thus from $v' = c' - g$ or (with Eq. (3)) $v' = Ac - g = A(v+g) - g$, we can write

$$v' = Av + (1 - A)(V + \gamma v)/(1+\gamma), \tag{5}$$

so that $v'^* v'$ can be computed straightforwardly; after averaging over the scattering angles $\theta, \phi$, noting that $\langle A \rangle_{\theta,\phi} = 0$ and $A^* A = 1$, we find

$$(1+\gamma)^2 \langle v'^* v' \rangle_{\theta,\phi} = 2V^* V + [(1+\gamma)^2 - 2\gamma] v^* v - 2(1-\gamma) V^* v$$

or

$$(1+\gamma)^2 \langle v'^* v' - v^* v \rangle_{\theta,\phi} = 2V^* V - 2\gamma v^* v - 2(1-\gamma) V^* v. \tag{6}$$

The left-hand side here is proportional to the energy gained by the electron in the collision: multiplying by $m/2$ gives

$$\langle \Delta T_m \rangle = m(1+\gamma)^{-2} [V^* V - \gamma v^* v - (1-\gamma) V^* v]. \tag{7}$$

The quantity on the right-hand side can be evaluated with the expressions given at the beginning of this section,

$$V = V_r + U, \tag{8a}$$

independent of time between collisions, but

$$v(t) = P(t)[v_r(0) + U], \tag{8b}$$

where $P$, which describes the action of the magnetic field on the electron velocity, is

$$P(t) = \begin{pmatrix} \cos\omega t & \sin\omega t & 0 \\ -\sin\omega t & \cos\omega t & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{9}$$

$\omega$ being the Larmor frequency. After averaging over directions (which causes the linear terms in one of the random velocities to drop out) and noting that $P^*P = 1$ we are left with

$$V^*V = V_r^*V_r + U_x^2$$

$$v^*v = v_r^*v_r + U_x^2$$

$$V^*v = U_x^2 \cos \omega t$$

(where we have simplified $U^*U$ to $U_x^2$ because gas velocity $U$ was assumed to be in the direction). Substitution of these expressions into Eq. (7) gives

$$\langle\Delta T_m\rangle = 2\gamma(1+\gamma)^{-2}\left[T_M^r - T_m^r + (1-\gamma)(1-\cos\omega t)\ \frac{1}{2}MU_x^2\right], \tag{10}$$

where we have written $T_M^r$ and $T_m^r$ for the kinetic energy of $M$ and $m$ due to the random motion: $T_M^r = MV_r^2/2$, etc. We note that, as expected, the energy gain of the electron depends on the time $t$ at which the collision takes place; for physically useful results we must average this over $t$ in such a manner that the mean interval between collisions will be $\tau$. This is done in Appendix A, the result being

$$\langle\cos\omega t\rangle = (1+\bar{\beta}^2)^{-1} \tag{11}$$

with

$$\bar{\beta} = \omega\tau/\ln 2$$

(we have written $\bar{\beta}$ because the symbol $\beta$ is usually reserved for $\omega\tau$). Thus Eq. (10) becomes

$$\langle\Delta T_m\rangle = 2\gamma(1+\gamma)^{-2}\left[T_M^r - T_m^r + (1-\gamma)\ \bar{\beta}^2(1+\bar{\beta}^2)^{-1}\ \frac{1}{2}MU_x^2\right].$$

This says that the energy gain of the electron in a collision will, on the average, be positive as long as the expression on the right-hand side is positive, or as long as

$$T_m^r < T_M^r + (1-\gamma)\ \frac{\bar{\beta}^2}{1+\bar{\beta}^2}\ \frac{1}{2}MU_x^2; \tag{12}$$

that is, the energy of the electron will continue to increase as the result of collisions until it exceeds the energy of the heavy particle by the second term on the right-hand side of Eq. (12). Note that as $\bar{\beta}$ varies from 0 to infinity, $\bar{\beta}^2/(1+\bar{\beta}^2)$ grows from 0 to 1, and the electron temperature (which of course is proportional to the electron kinetic energy) will not exceed the gas temperature at all when $\bar{\beta} = 0$ ("magnetic deflector" or "Faraday mode operation") but will reach its maximum possible value when $\bar{\beta}$ is large ("magnetic sieve," "Hall mode operation"). Other convenient ways of writing Eq. (12) are

$$T_m^r < T_M^r + \frac{\bar{\beta}^2}{1+\bar{\beta}^2}\ T_M^U \tag{13}$$

or

$$T_m^r < T_M^r\left(1 + \frac{\bar{\beta}^2}{1+\bar{\beta}^2}\ \frac{U_x^2}{V_r^2}\right).$$

(Here $\gamma$ has been neglected with respect to unity, and $T_M^U$ has been designated as the kinetic energy of a heavy particle moving with a velocity equal to the directed velocity $U_x$ of the gas.) In these expressions, it is appropriate to interpret $T$ as either the kinetic energy or as temperature.

To obtain our final result, we consider what happens to a hot gas as it expands through a nozzle, thereby acquiring a gross velocity while cooling down. The random velocity $V_r^0$ of a given atom breaks up into two components, a smaller random velocity $V_r$ and a directed velocity $U$:

$$V_r^0 \to V_r + U ,$$

which after squaring becomes

$$V_r^{0*} V_r^0 \to V_r^* V_r + U^* U + 2V_r^* U .$$

The last term vanishes when averaged over all particles; hence

$$T_M^0 = T_M^r + T_M^U , \tag{14}$$

where $T$ can again mean either kinetic energy or temperature. Comparing this with Eq. (13) we see that

$$T_m^r \leq T_M^0 , \tag{15}$$

i.e., that the nonequilibrium electron temperature never exceeds the temperature that the gas had before expanding the nozzle, and can reach that temperature only if $\bar{\beta} \to \infty$ (extreme Hall case).

The derivation of the preceding paragraph would be unchanged if, instead of setting a stationary gas in motion, we thought of bringing the moving gas to a stop; therefore, $T_M^0$ is in fact the stagnation temperature of the gas. We have thus shown that the nonequilibrium electron temperature induced magnetically cannot exceed this (5).*

In the preceding derivation, a number of simplifications have been made. As explained, the many complex interactions involving the various species of particles and the magnetic field have been lumped into the two parameters, $\omega$ (Larmor frequency) and $\tau$ (time between hard-sphere collisions). Spatial inhomogeneities have been ignored; and a single mean energy has been used for each species rather than a Maxwellian distribution about the mean, this matter taken care of by introducing the temperature concept, with its implied distribution, in the end. While thus the results should not be taken as applying with precision to each individual particle in the gas, one can have confidence in the overall result (Eq. (15)).

*The possibility of higher temperatures is predicted in Ref. 5; that derivation assumes that the parameter $K$ (equal to $E_y/UB$ in one case and to $E_x/UB\beta$ in another) can be adjusted independently of $\beta$ and $U$, whereas the induced electric field $E$ is in fact determined by these quantities, and it assumes the validity throughout the interior of the channel of the conditions $J_x = 0$ (for segmented electrode configuration) or $E_y = 0$ (for opposite electrodes shorted) -- conditions which the respective electrode configurations assure only near the electrodes themselves.

Coulomb Field Model

No new results are obtained in this section, but the ones of the preceding section are rederived from a model which gives the appearance of being diametrically opposite to the previous one: whereas in the previous model we assumed that all interactions between members of different species were mediated by hard-sphere collisions between collisions between electrons and neutrals, we now assume a wholly collisionless regime and electrostatic (coulomb) interaction providing the mode of communication between particles. Since collisions become infrequent as $\tau$ or $\overline{\beta}$ increase, the results to be obtained in this section should agree with what the preceding section gives in the limit $\beta \to \infty$. This will indeed be found to be true. In addition to producing this check, the present method provides a bridge to the more conventional viewpoints (2) by explicitly showing the source of the induced electric field that, in the conventional terminology, produces the acceleration of the electrons.

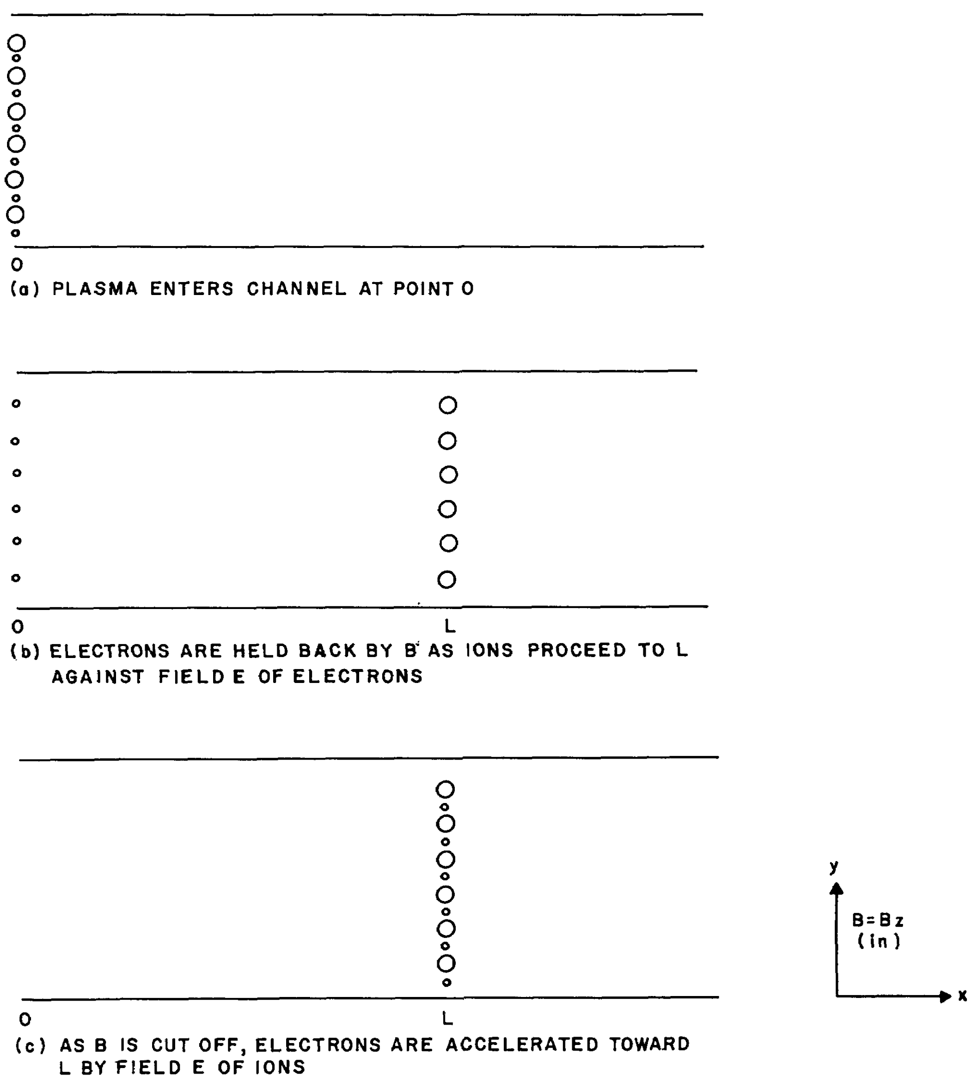


Fig. 5 - Coulomb field model

Consider, then, a collision-free ionized gas moving with gross velocity $U = U_x$ in a magnetic field $B = B_z$. The ions and neutrals are unaffected by this magnetic field and move forward, but the forward motion of the electrons is stopped by the magnetic field, which causes them to move in Larmor circles, or spirals, with no net motion in the $x$ direction (Fig. 5b). The sheet (in the $y$-$z$ plane) of charged ions moving away in the $x$ direction thus provices an electric field $E$ on the electrons (this is precisely the "Hall" field in the usual terminology of the MHD generator literature). Now the motion of a charged particle in crossed magnetic and electric fields is well known: a drift in the direction perpendicular to both $B$ and $E$ is superimposed on the spiral motion (6). For our purposes, the actual motion of the particles need not be found, but the three equations of motion

$$m\dot{\vec{v}} = e(\vec{v} \times \vec{B} + \vec{E})$$

need be integrated only once to give the components of $\vec{v}$ and from that the kinetic energy of each electron. In our model, where $\vec{B} = B_z$ and $\vec{E} = E_x$ are constant (the latter because it is due to a sheet of charge, which produces an electric field that is independent of distance) and $\vec{v}$ is given by Eqs. (8b) and (9), we find

$$v^*v = v^*(0)v(0) + 2\left(\frac{E_x}{B_z}\right)^2 - 2v_y(0)\left(\frac{E_x}{B_z}\right) + 2\left(\frac{E_x}{B_z}\right)\left\{v_x(0) \sin \omega t + \left[v_y(0) - \left(\frac{E_x}{B_z}\right)\right] \cos \omega t\right\}.$$

The last term in the braces averages to zero over any cycle and can therefore be ignored. We then see that the excess of the kinetic energy of the electron over its original value increases with decreasing $B$; the maximum obtainable can therefore be computed by letting $B \to 0$.

The applicable model is therefore the following, as illustrated by Fig. 5: with $B$ on, the sheet of ions moves away in the $x$ direction (and the sheet of electrons remains, spiraling, behind) until the space charge, or "Hall Field," $-E$ brings the ions to a stop, a distance $L$ from the electrons. If the magnetic field $B$ is then cut off, the electron sheet will move towards the ions on account of the $E$ field (the attraction of the ions) and the maximum energy attainable by the electrons will then be equal to the kinetic energy that they obtain when they reach distance $L$.

The actual computation is very easy: the energy of the $N$ ions due to the motion in the $x$ direction is $N(MU^2/2)$, and the point $L$ they can reach before that kinetic energy is balanced by the field $-E$ of the electron sheet is given by

$$\int_0^L eE\,dx = N(MU^2/2)$$

or (16)

$$eEL = N(MU^2/2).$$

Then, after the electrons are permitted (by cutting off $B$) to follow to $L$, the electrons' energy will be

$$\int_0^L F\,dx = \int_0^L eE\,dx = eEL,$$

which by Eq. (16) is $N(MU^2/2)$, or $MU^2/2$ per electron. We have thus shown that the maximum increase in energy of an electron is equal to $MU^2/2$ in full agreement with Eq. (15) in the limit $\bar{\beta} \to \infty$.

## CONCLUDING REMARKS

If the working fluid of an MHD generator is to be operated at temperatures below 1500°K, adequate power can be attained only if the ionization is enhanced above its thermodynamic equilibrium value. Several schemes for obtaining such ionization have been proposed and/or tested (4,7,8): irradiation by ultraviolet, x-rays, or neutrons; an rf discharge; and raising the temperature of the electrons present, by the use of the magnetic field itself, to a value high enough to produce more ionization. In this report, the last of these has been considered; it has been found that the electron temperature so attainable cannot exceed the stagnation temperature of the gas, which is the same as the temperature that the gas had when at rest before being expanded through a nozzle. This limit suggests that magnetically induced nonequilibrium electron temperatures can only partly compensate for low gas temperatures and that very high temperatures for the reactor that is to heat the gas cannot be circumvented.

## ACKNOWLEDGMENTS

This work was done while the writer was working with the Power Branch of the Office of Naval Research. I wish to thank Dr. Ralph Roberts, Mr. John A. Satkowski, and Dr. Talbot A Chubb for useful discussions.

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## Appendix A

## DERIVATION OF EQ. (11)

Let $n(t)$ be the number of particles that have not suffered a collision before time $t$. Let the number of collisions be proportional to the number of particles remaining as well as to the time interval,

$$dn = -an\ dt \tag{A1}$$

(by analogy with the well known situation in radioactive decay). The solution of Eq. (A1) is

$$n(t) = n(0)\ e^{-at} . \tag{A2}$$

The condition that the mean lifetime before collision be $\tau$ demands that

$$n(\tau) = n(0)/2 .$$

This enables us to find from Eq. (A2) that

$$a = (\ln 2)/\tau . \tag{A3}$$

The fraction of $n(0)$ colliding in an interval $dt$ is $-n(0)^{-1}\,dn/dt$, which is, from Eq. (A2), $ae^{-at}$. This fraction is also the probability of a collision occurring at $(t,\ t+dt)$. The average value of $\cos\omega t$ averaged over all collision times is therefore

$$\langle\cos\omega t\rangle = \int_0^\infty \cos\omega t\ a\,e^{-at}\,dt$$

$$= (1+\bar{\beta}^2)^{-1},$$

where

$$\bar{\beta} = \omega\tau/\ln 2 .$$

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| | |
|---|---|
| 1. ORIGINATING ACTIVITY *(Corporate author)*<br>Naval Research Laboratory<br>Washington, D.C. 20390 | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

MAGNETICALLY INDUCED NONEQUILIBRIUM ELECTRON TEMPERATURES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on one phase of the problem.

5. AUTHOR(S) *(Last name, first name, initial)*

Rosenstock, Herbert B.

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| November 23, 1966 | 14 | 8 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>NRL Problem P03-07<br>b. PROJECT NO.<br>RR 008-03-46-5676<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>NRL Report 6456<br>9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* |

10. AVAILABILITY/LIMITATION NOTICES

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|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Department of the Navy<br>(Office of Naval Research),<br>Washington, D.C. 20360 |

13. ABSTRACT

For operation of an MHD generator at low temperatures, various methods have been proposed to enhance the ionization and hence the conductivity. This report considers the scheme in which the electrons present in an MHD generator are accelerated by the magnetic field itself (to a "magnetically induced nonequilibrium temperature") preparatory to producing additional electrons by impact ionization. A model for the flow of a partially ionized gas in an MHD generator that combines extreme mathematical simplicity with at least qualitative physical realism is used. The derivations show that the electron temperatures attained cannot exceed the temperature that the gas had before part of its kinetic energy was converted into motion along the channel; that is, the magnetically induced nonequilibrium electron temperature cannot exceed the stagnation temperature of the gas, which is equal to the temperature of the gas at rest before being expanded through a nozzle.

DD FORM 1 JAN 64 1473



Security Classification

| 14. KEY WORDS | LINK A ROLE | LINK A WT | LINK B ROLE | LINK B WT | LINK C ROLE | LINK C WT |
|---|---|---|---|---|---|---|
| Magnetic fields | | | | | | |
| Electrons | | | | | | |
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